MANEUVERING PERFORMANCE OF A FERRY AFFECTED BY RUDDER AREA AND SPEED

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SUMMARY

The aim of the study is to determine the effect of rudder area and speed on a ferry ship maneuvering performance, especially during the turning circle and zigzag maneuver. MATLAB-simulink was used to simulate turning circle and zigzag maneuver. The simulation utilized model based on the concept of Mathematical Modelling Group (MMG) includes testing/separating components of the hull equations, propeller and rudder as well as the interaction among them (hull, propeller and rudder). The result of simulation indicated that rudder dimension and ship speed affect both turning circle and zigzag maneuver of the ferry reasonably.

NOMENCLATURE

ϕ	Roll angle
ρ	Density of water
β	Drift angle
δ	Rudder angle
ψ	Course angle or heading
Λ	Rudder aspect ratio
ε	Phase angle
a_H	Rudder to hull interaction coefficient
A_D	Advances diameter
A_R	Rudder area
B	Ship breadth
B_{44}	Added inertia of roll motion
C_1, C_2, C_3	Constants for open water propeller
CB (Cb)	Block coefficient
D_P	Propeller diameter
D_T	Tactical diameter
f_a	Gradient of the lift coefficient of rudder
F_N	Normal force acting on rudder
G	Center of gravity of vessel
I_{ZZ}	Moment of inertia with respect to the z-axis
J	Advance coefficient
J_{ZZ}	Added moment of inertia around z-axis
K	Moment with respect to the x- axis
K_Q	Torque coefficient
K_R	Momen of rudder
K_T	Thrust coefficient
LOA	Ship length overall
LBP	Length of between perpendiculars
m	Mass of ship
n (rpm)	Propeller revolution
V_A	Advance velocity (m s^{-1})
N	Moment with respect to the z- axis
P	Propeller pitch
P/D_P	Propeller pitch ratio
t_p	Trust deduction factor
T	Draught of ship
r	Turning rate or angular velocity
r'	Non-dimensional turning rate
u	Velocity in x- direction (surge)
$\dot{u}$	Acceleration in x-direction (surge)
U	Vessel velocity
U_R	Rudder inflow velocity
v	Velocity in y-direction (sway)
$\dot{v}$	Acceleration in y-direction (sway)
w_p	Effective wake fraction coefficient at propeller
w_{p0}	Effective wake fraction coefficient of propeller in straight running
x, y, z	Ship-fixed co-ordinate system
x_0, y_0, z_0	Space-fixed co-ordinate system
x_H	The distance between the centre of gravity of hull ship
x_G	Centre of gravity (positive if forward of amidships)
x_R	The distance between the centre of gravity of ship and centre of rudder lateral force
X	Force in x-direction
X_0, Y_0	Forces in the x_0- or y_0- direction
X_P	Propeller thrust
X_R	Rudder force in x -direction
Y	Force in y-direction acting on ship
Y_R	Rudder force in x -direction
Z	Number of propeller blades

1. INTRODUCTION

The number of ferry carrying trucks, bus, car, motor cycle, passenger etc., is increasing in Indonesia. The operation could improve national economic growth. In ferry building, from design to delivery, several tests must be conducted, particularly the operation ability.

Maneuvering characteristics are very important criteria to make sure that the ferry can operate in certain situation and location. Maneuverability is very critical aspect especially in harbour and offshore such as tow and tug to avoiding collision. Noor [1] suggested that maneuverability is an important characteristic that must be predicted during the early design of ship. The simulation of ship maneuvering has now progressed quite well and is very useful in designing the ship [2].

Ship maneuverability is also directly related to navigation safety and economy. In some restricted waters, marine accidents can occur if the ability to maneuver the ship is not adequate. On the other hand, the dynamic stability of ships with poor course could only maintain its position by using a control device as often as possible. The consequences for a ship like this is not just a voyage being longer than planned, but also more energy is consumed by the control device [3].

Many accidents are caused by a ship with low maneuvering quality.[4].

Ship designer need to consider the existing rules, both nationally and internationally. In 2002, the International Maritime Organization (IMO) [5] issued a Resolution MSC.137 (76) "Standards for Ship Maneuverability", to develop safety standards and to ensure the safety of cruise ship operating at sea.

In principle, maneuverability is greatly influenced by hull design, propulsion, rudder and steering system. A number of these elements are in a direct significantly influence the hydrodynamic force and moment when ship maneuvers [6].

2. METHODOLOGY

2.1 Mathematical Model

In analyzing the ship maneuvering through computer simulation, mathematical model is important to be developed including hydrodynamic coefficients derived here. In this study, a mathematical model based on the equations of motion, Eq. 1 of ship developed (4-degree of freedom) the surge, sway, yaw and roll motions.

The mathematical model for maneuvering motion can be described by Eq. 1 using the ship coordinate system, Fig.1.

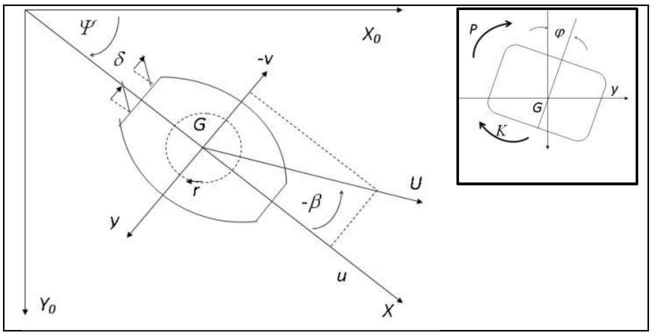

Fig. 1. Ship Coordinate System

$$
\begin{aligned}
X &= m(\dot{u} - rv) \\
Y &= m(\dot{v} - ru) \\
N &= I_{ZZ}\ddot{\psi} \\
K &= I_{XX}\dot{p}
\end{aligned}
\qquad (1)
$$

The notation of u, v and r are velocity components at centre of gravity of ship (C.G). U represents resultant of the ship speed. X, Y, N and K represent the hydrodynamic forces and moment acting on the C.G. of the hull These forces and moments can be defined separately into the different elements of physical force and moment of the ship in accordance with the concept developed by Ogawa and Kansai [7] as follows:

$$
\begin{aligned}
X &= X_H + X_R + X_P \\
Y &= Y_H + Y_R + Y_P \\
N &= N_H + N_R + N_P \\
K &= K_H + K_R + K_P
\end{aligned}
\qquad (2)
$$

Where, the subscript H, P and R refer to hull, propeller and rudder respectively. Force and moment induced by hull (X_H, Y_H, and N_H) in principle is an approximation of polynomiual regression β and r'. Furthermore the coefficients of these equation can be termed as derivative of the hydrodynamic coefficients. The equation can be expressed by Eq 3:

$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\
Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3) \\
N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr} r'^3)
\end{aligned}
\qquad (3)
$$

where :
$\beta = \tan^{-1}(v/u)$ and $r' = r(L/U)$

and heeling moment equetion expressed by Eq 4:

$$
K_H = -z_H Y_H - B_{44}\dot{\phi} - C_{44}\phi \qquad (4)
$$

where :

$$
\begin{aligned}
z_H &= OG - h \\
C_{44} &= gm\overline{GM} \\
B_{44} &= \frac{2}{\pi}\sqrt{gm\overline{GM}(I_{XX} + J_{XX})}
\end{aligned}
$$

According to Kijima [8], equation force and moment induced by propeller and rudder can be expressed by the eq. 5:

$$
\begin{aligned}
X_P &= (1 - t_P)\rho K_T D_P^4 n^2 \\
Y_P &= 0;\ N_P = 0;\ K_P = 0
\end{aligned}
\qquad (5)
$$

where:

$K_T(J_P)=C_1+C_2J_P+C_3J_P{}^2$

$J_P=U\cos\beta(1-w_P)/(nD_P)$

Force and moment on rudder area ($X_{R,}$ Y_R, N_R and K_R) can be expressed by Eq. 6:

$$\begin{aligned} X_R &= -2(1-t_R)F_N \sin\delta \\ Y_R &= -2(1+a_H)F_N \cos\delta \\ N_R &= -(x_R+a_H x_H)F_N \cos\delta \\ K_R &= -z_R Y_R \end{aligned} \qquad (6)$$

where:

$$F_N = \tfrac{1}{2}\rho A_R f_\alpha U_R^2 \sin \alpha_R$$

$$f_\alpha = 6{,}13\Lambda/(2{,}25+\Lambda)$$

$$U_R = \sqrt{u_R^2 + v_R^2}$$

$$\alpha_R = \delta - \tan^{-1}\left(\frac{-v_R}{u_R}\right)$$

$$u_R = \varepsilon(1-w)u \times \sqrt{\mu\left\{1+\kappa\left(\sqrt{1+(8K_T/\pi J^2)}-1\right)\right\}^2 + (1-\eta)}$$

$$v_R = \gamma_R(v - r l_R)$$

2.2 Programming and Simulation

According to IMO standard, the assesment of the ship maneuvering is analysed based on swept path. There are two methods for this purpose. Firstly, free running model test. Secondly, computer simulation using mathematical model. Here, the investigation has been carry out using time domain simulation program based on MATLAB-Simulink. The swept path of ship can be obtained by double integrating the acceleration of the ship in surge, sway, yaw and roll axis of mathematical model that include the hydrodynamic derivatives [6].The step integration can be expressed:

$$\begin{aligned} &Surge \quad : X = m(\dot{u} - rv) \\ &Accelerati\quad on : \dot{u} = (X/m) + rv \\ &Velocity \quad : u = \int \dot{u}\, dt \\ &Position \quad : x = \int u\, dt \end{aligned}$$

Then by the same method the motion integration process for sway, yaw and roll were performed. The next simulation is developed and analyzed through computer simulation in MATLAB-Simulink software.

2.3 Ship Operation Scenario

To determine the effect of rudder area and speed variations on a ferry ship maneuvering performance, the scenario role in the operation of ships are: 1) The vessel is operated with variation in rudder area (A_R = 1.632 m^2, A_R = 1.819 m^2 and A_R = 2.078 m^2). 2) The vessel is operated with variation of speed (V = 2 knots, 6 knots and V = 10.5 knots).

Tables 1, 2 and 3 show the ship particulars, parameters of the propeller and rudder, hydrodynamic derivatives coefficient of KMP Sultan Murhum respectively. In support maneuver, ship was equipped with two conventional propulsors (FPP) and 2 conventional rudders, mounted behind the ship. A number of parameters in the prediction of propulsion using Holtrop method [9][10]. Rudder area parameters obtained from field data, A_R = 2.078 m2 (original) and A_R = 1.632 and 1.819 m^2 (modified). Further hydrodynamic coefficients predicted by the derived regression equation developed by Yoshimura and Ning [11] and Yoshimura [12].

Table 1. Ship particulars

Parameter	Value	Unit
LOA	36.4	m
LBP	31.5	m
LWL	35.73	m
.B	8.7	m
H	2,.65	m
T	1.65	m
V	10.5	knot
Cb	0.63	
Δ	321.8	ton

Table 2. Propeller and rudder parameters

Parameters	Value	Unit
Dp	1.1	m
N	2	
Z	2	
A_E/A_O	0.40	
RPS	8.578	Rev/s
w	0.219	
t	0.142	
Jp	0.499	
K_T	0.230	
A_R,	2.078	m^2

Table 3. Hydrodynamic derivative coefficients

Coeficient	Value	Coeficient	Value
		Y'β	0.4629
X'o	-0.00743	*Y'r-m'x*	0.0348
X'ββ	-0.1477	*Y'βββ*	1.2
X'βr-m'y	0.06604	*Y'ββr*	-0.5
X'rr	0.03	*Y'βrr*	0.34
X'βββ	1.183	*Y'rrr*	-0.04
N'β	0.1397	*1-tr*	
N'r	-0.05592	*αh*	0.8478
N'βββ	0.3	*ε*	1.0306
N'ββr	-0.33	*K*	0.3986
N'βrr	0.01	*l'R*	0.9042
N'rrr	0	*γr*	0.4884

3. RESULT AND DISCUSSION

3.1 Effect of Rudder Area Variatons.

Fig 2 shows the result of the simulation for turning circle on ship operated. The tactical diameters (D_T) and advances (A_D) manuever of the ship were calculated. It is found that the tactical diameter of the vessel for rudder area of 2.078 m^2 at a speed of 10.5 knot with a full draught 1.65 m is 73 m, 2.42 times the vessel length, of 31.5 m. This tactical diameter meets the required IMO criterion of not more than five times the ship length. The advance is 65.7 m or 2.1 times the vessel length. This value is also within the IMO criterion of 4.5 times ship length.

Fig. 2 shows the comparison of the turning circle of the two rudder area madified (A_R = 1.8191 m^2 and 1.632 m^2). It shows that the tactical diameter increased are 2.09% for A_R= 1.819 m^2 dan 3.66 % for A_R = 1.632 m^2 compaired with original rudder area (A_R = 2.078 m^2). Fig. 3 shows the history of the heel angle during turning cicle maneuvering. It is shows that the heel angle reduiced diminishes as rudder area reduices. At the rudder area of 2.078 m^2, which heel angle is 3.21^o while 3.15^o and 3.10 at rudder area of A_R = 1.819 m^2 and 1.632 m^{2o} respectively. This value is also within the IMO criterion (<10^o). It is found that the rudder area dimension has effect on the maneuvering performances of a ferry ship.

Fig. 4 show the result of the simulation for the zigzag maneuver 20/20 of the ship was simulated. The horizontal and vertical axes respectively express time and heading angle (ψ). It shows that the heading angle of original of rudder area dimension (A_R = 2.078 m^2) has the bigger overshoot angle as compared to the modified rudder area (A_R = 1.819 m^2 and 1.632 m^2). At rudder area 2.078 m^2, which takes time 5.5 second for 1st *overshoot* and 14 seconds fasten for 2nd overshoot with the heading angle of 1.5^o and 3.5^o respectively. It shows that the time used and heading angle reduced diminishes as rudder area reduces. Results can be seen in Table 4.

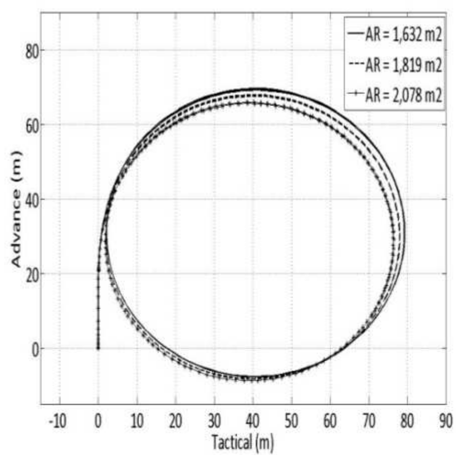

Fig. 2. Turning circle with rudder area variations

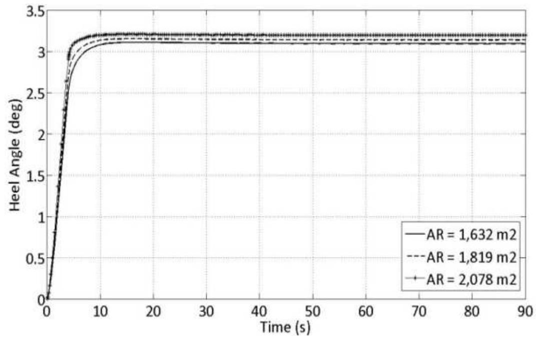

Fig 3. Heel angle on turning circle with rudder area variations

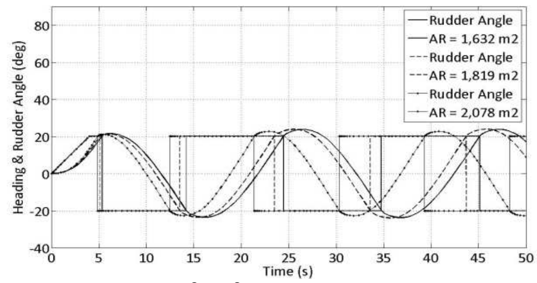

Fig 4. Zigzag 20^o/20^o with rudder area variations

Table 4. Summary of simulation result of turning circle and zigzag maneuver with rudder area. The large the rudder area the greather the sreering force produeced, in line with smaller tactical and advance.

Table 4. Simulation results, turning circle and zigzag at three different rudder area.

Parameter	IMO Criteria	Rudder Area (A_R), m²		
		2.078	1.819	1.632
D_T, m	< 5 L	76.3	77.9	79.1
A_D, m	< 4.5 L	70.5	67.5	65.5
Ø, rad	<10^0	0.7	1.1	1.49
1st Overshoot, ψ, deg.	< 25°	1.5	1.4	1.2
1st Overshoot, *s*, second		5.5	5.9	6.3
2nd Overshoot , ψ, deg.	< 40°	3.5	3.6	2.6
2nd Overshoot, *s*, second		14	15.7	16.5

3.2 Effect of Speed Variatons.

Fig 5 shows the comparison result of the simulation for turning circle with speed variations, namely V = 2 knots, V = 6 knots, and V = 10.5 knots respectively with draught of 1.65 m and rudder area of 2.078 m^2. It shows that the tactical diameter and advanced reduced diminishes as speed reduces. Tactical diameter and advanced increased are 7.3 and 19.98% at V=2 knots dan 1.96 and 7.77% at V = 6 knots compared with full speed (V = 10.5 knots). Fig. 6 shows the history of the heel angle during turning cicle maneuvering. It shows that the heel angle reduced diminishes as speed reduces. At V= 10.5 knots, heel angle is 3.21^o while 3.15^o and 3.10 ^{o} at V = 6 and 2 knots respectively. This value is also fullfil the IMO criterion (<10^o). It is found that the ship speed has effect on the maneuvering performances of the ferry, proporsionally.

Fig. 7 shows that the comparison results of the simulation for the zigzag maneuver 20/20 with speed of ship. The horizontal and vertical axes respectively express time and heading angle (ψ). It shows that the heading angle of full speed (V=10.5 knots) has the bigger overshoot angle compared with the other speeds (V=6 and V=2 knots). At V= 10.5 knots, it takes 5.5 second for 1st *overshoot* and 14 seconds faster for 2nd overshoot with the heading angle of 1.5^o and 3.5^o. It shows that the time used and heading angle find reduced diminishes as rudder area reduces. Results can be seen in Table 5. The higher the speed the grather the force by propeller. This is in line with bigger tactical diameter and advance.

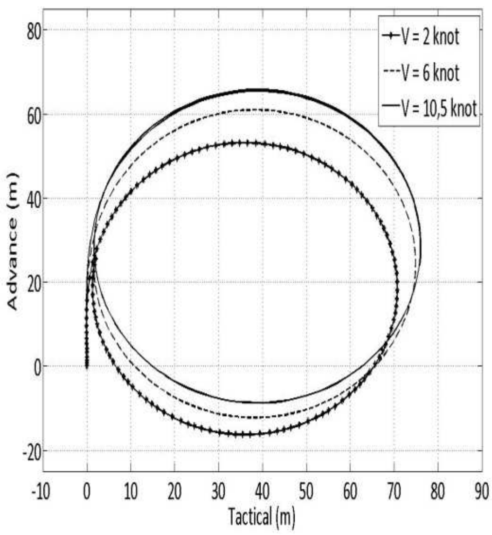

Fig. 5. Turning circle withspeed variations

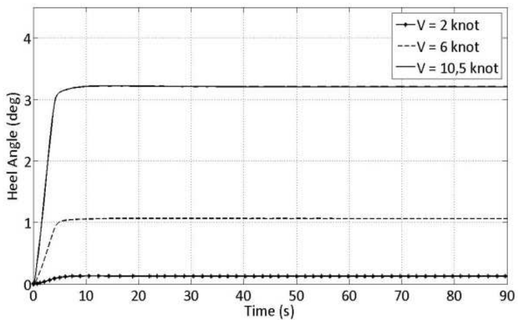

Fig 6. Heel angle on turning circle with speed variation

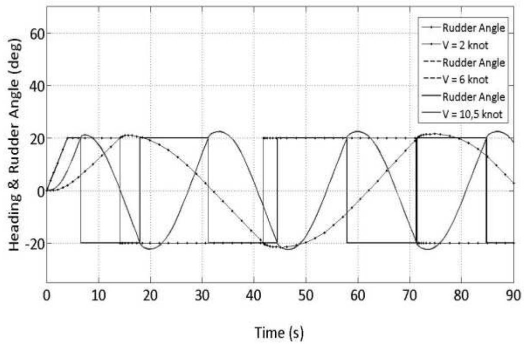

Fig 7. Zig-zag 20^o/20^o with speed variations

Table 5. Summary of simulation result of turning circle and zigzag maneuver at three different speeds.

Parameter	IMO Criteria	Speed (knot)		
		10,5	6	2
D_T, m	< 5 L	76.3	74.8	70.7
A_D, m	< 4.5 L	65.6	60.5	52.5
Ø, rad	<10^0	3.2	1.1	0.1
1st Overshoot, ψ, deg.	< 25°	1.2	1.2	1.0
1st Overshoot, *s*, second		5.5	7.4	16.5
2nd Overshoot , ψ, deg.	< 40°	2.6	2.3	1.6
2nd Overshoot, *s*, second		14	19.8.7	45.1

4. CONCLUSIONS

Based on the analysis, during turning circle and zigzag maneuver the following conclusions have been made:

1. The larger the rudder area the greater the steering force produced.

2. The faster the ship the greater the force induced by propeller.

5. ACKNOWLEDGEMENTS

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